Nonlinear Internal Waves - A Wave-Tracking Experiment to Assess Nonlinear Internal Wave Generation, Structure, Evolution and Dissipation over the NJ shelf / Analysis

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LONG-TERM GOALS

The thrust of this project is the investigation of non-linear internal waves which appear as waves of depression when propagating on a near-surface interface and as waves of elevation when propagating on a near-bottom interface. Waves of depression will initiate the generation of waves of elevation as they propagate into shallow water where the interface depth below the surface nears its height above bottom. We have had the good fortune to observe (by shipboard wave-tracking and from bottom-moorings) both waves of depression and of elevation propagating inshore from the Oregon shelf break into shallow water. We have now also had the further good fortune to make systematic and comprehensive studies of the generation, structure, evolution and dissipation of non-linear internal waves over the New Jersey shelf within the context of the heavily-instrumented combined acoustic / environmental array deployed in summer 2006.

The long-term goal of this program is to understand the physics of small-scale oceanic processes including internal waves, hydraulics, turbulence and microstructure that act to perturb and control the circulation in coastal oceans and, in doing so, affect the propagation of sound and light. Ongoing studies within the **Ocean Mixing Group** at OSU emphasize observations, interaction with turbulence modelers and an aggressive program of sensor / instrumentation development and integration.

OBJECTIVES

Specific objectives for this proposal are to:

- clarify the detailed internal structure of NLIWs from SW06 observations, previous observations over the Oregon shelf and from turbulence measurements made on Niiler-type drifters in the South China Sea;
- coordinate with J. Nash to define a consistent approach for computing wave displacement and energetics using the comparative strengths of both moored (spatially sparse; temporally resolved) and shipboard observations (well-resolved but only for a limited number of waves during a limited time period);
- define the wave energy balance along its propagation path;

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- describe and quantify the structural and energetic evolution of the relatively slowly-propagating waves as they shoal over the gentle NJ shelf – and compare this with the evolution of rapidly-propagating SCS waves as they shoal over steeper terrain;
- investigate the effects of wave-wave and group-group interactions;
- assist D. Rouseff and DJ Tang (APL/UW) in defining a deterministic representation of NLIW propagation from joint medium-frequency acoustic / shipboard wave-tracking studies;
- assist M. Badiey (U Delaware) in an analysis of sound focusing / defocusing due to propagating nonlinear internal waves;
- assist Andone Lavery (WHOI) in defining the acoustic frequency/wavenumber backscatter spectrum of turbulence using coincident acoustic / turbulence observations.

APPROACH

For NLIWI/SW06, we combined acoustic flow imaging techniques with shipboard ADCP and microstructure profiling measurements (using CHAMELEON). This has permitted an observational view of shoreward-propagating internal solitary waves (both near the surface and near the bottom) not previously achieved. These observations have been supplemented by deployment of 4 bottom landers outfitted with upward-looking ADCP (to obtain water column velocity profiles), acoustic Doppler velocimeters (to detect the turbulent component of the velocity signal at 1 m height above the seafloor) and CTD. Three of these landers were also outfitted with high-resolution pressure sensors.

For NLIWI/SW06, we collaborated with Andone Lavery (WHOI), who deployed a high-frequency broadband acoustic backscattering system intended to obtain a remote measure of the turbulence that we coincidentally sample *in situ* using CHAMELEON. The resultant data set is extensive and offers a new look at the internal structure of the waves. We also coordinated measurements to support acoustics experiments during SW06 to examine sound focusing / defocusing due to nonlinear internal waves (M. Badiey, U. Delaware) and to examine the effects of nonlinear internal waves on short range propagation of mid-frequency sound (DJ Tang, APL/UW).

WORK COMPLETED

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From 30 July 2006 to 26 August 2006, we made shipboard observations of NLIWs within the SW06 mooring array from the *RV Oceanus*. These observations consist of:

- more than 7500 Chameleon turbulence profiles of temperature, salinity, density, turbulence dissipation rate (ε) and oprical backscatter;
- hull-mounted 300 kHz Acoustic Doppler current profiles at 5 s, 2 m resolution;
- over-the-side, near-surface 1200 kHz ADCP measurements at 2 s, 1 m resolution – this configuration provided data from about 2.5 m depth, at least 5 m closer to the surface than can be obtained from a unit mounted in the ship's transducer well. Such data are especially critical in relation to radar studies of the sea surface;
- high-frequency (120 kHz) echosounder – these data provide qualitative imagery of the waves but are also calibrated and thus can be used to assess the turbulence contribution to the narrow-band acoustic field;
- X-band radar recorded continuously at 30 s intervals.

These wave-tracking observations yielded 26 named waves, most of which were tracked from or shortly following generation to the point where their energy had decreased below detection levels. A

file of named wave time/positions has been distributed and used by experiment PIs and is available on SW06 and OSU Ocean Mixing websites. ADCP data have been processed and shared with all who have made requests (primarily those investigating magnetic anomalies and surface radar signatures). A full data set is available on SW06 and Ocean Mixing websites.

Four bottom landers were deployed as part of the intensive SW06 array. And three χpods were deployed on one of the Niiler-style drifters deployed by Luca Cenurioni and Peter Niiler in the South China Sea in May 2007 as part of the South China Sea component of NLIWI.

Several papers were published, including an overview of both acoustics and physical oceanography aspects of SW06 in *Oceanography* (Tang et.al., 2007). Two other review papers were published that benefited from this project, including analysis and figures (Moum, Nash and Klymak, 2008; Moum and Rippeth, 2009). Papers more specific to SW06 are listed under Publications.

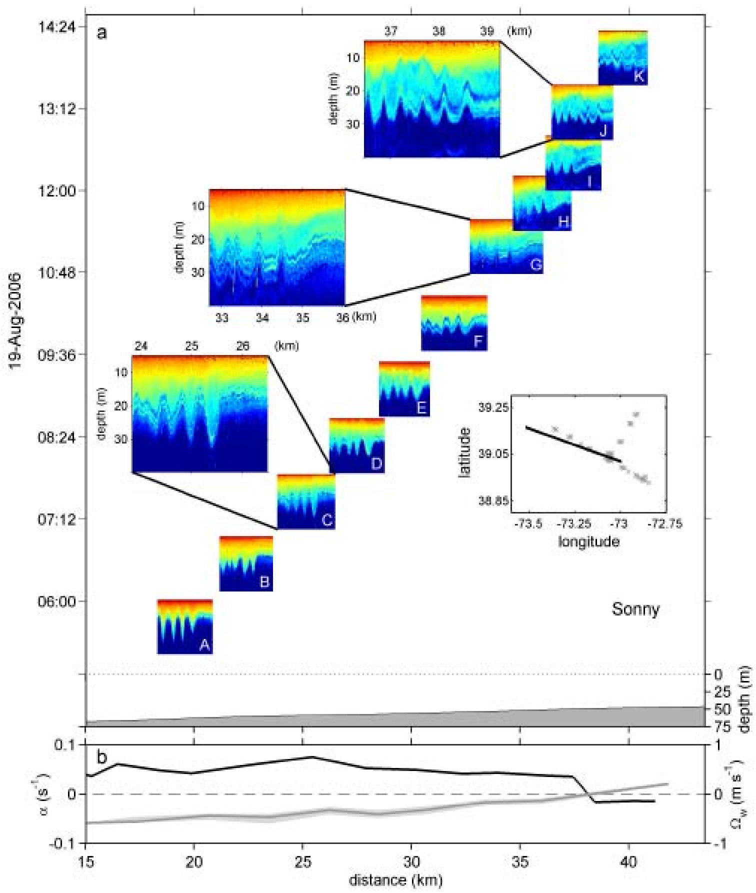

Figure 1 – Polarity reversal in nonlinear internal waves. a) Acoustic backscatter transects taken perpendicular to wave front for Wave Sonny. Each series has been corrected for Doppler shifting so that waves may be viewed in a spatial frame with minimal distortion. The horizontal axes for each panel (A–K) are accurately scaled to the distance axis; the vertical axes for (A–K) are centered about the time of the lead wave. Select transects are enlarged in order to highlight details of structural evolution. For reference purposes, water column depth is plotted at the bottom. Lower right inset shows mooring array and approximate wave path (black line). b) The predicted critical point defined by the parameter, α, is plotted in gray on the left-hand side, and the observed transition point given by the sign of the maximum integrated wave vorticity, Ω_w, is plotted in black on the right-hand side (from Shroyer et al, 2009a).

RESULTS

1. We have documented patterns of structural changes that nonlinear internal waves undergo as they propagate long distances (100s of wavelengths) into shallow water. Nearly symmetric waves develop consistent asymmetries in which the leading edge accelerates causing the front face to broaden while the trailing edge remains steep. This ultimately results in polarity reversal in which an elevation wave forms from the depression wave (Figure 1). The transition is diagnosed by the integrated wave vorticity (which changes sign as the wave's polarity changes sign), and is predicted by simple theory, when properly evaluated using observed shear and stratification (Shroyer et.al., 2009a).

2. It is clear that waves with more complicated structure than elevation / depression waves are part of the wave hierarchy on continental shelves (Figure 2; Moum, Nash and Klymak, 2008). These may be referred to as mode-2, or varicose, waves. They are energetically weak by comparison to the dominant depression waves on the NJ shelf (Shroyer etal 2009b).

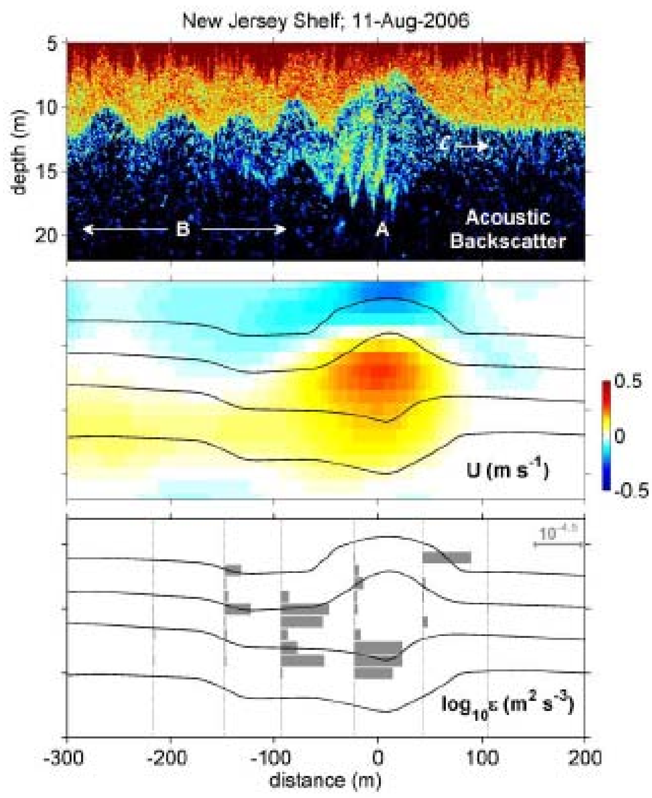

Figure 2 - upper panel – acoustic backscatter; middle panel – onshore wave velocity, U, with isopycnals contoured; lower panel, turbulence dissipation rate, from shipboard measurements over the New Jersey shelf in 85 m water depth. Shoreward direction is to the right. (Shroyer etal, 2009b).

3. We have measured the seafloor pressure signal of nonlinear internal waves (Moum and Nash, 2008).

4. We have made an assessment of the vertical heat flux and lateral transports due to nonlinear internal waves on the NJ shelf (Shroyer etal, 2009c; Fig. 3). In particular, the cross-isopycnal heat flux due to the waves is critical to maintenance of the mixed layer temperature over the shelf. Instantaneous cross-isopycnal heat fluxes due to the waves is O(1000) W m^{-2}. While the waves are present at a location on the shelf < 5% of the time, they contribute 50% of the cross-isopycnal heat flux, which is equivalent to the surface heat flux in August 2006. In the absence of the waves, the mixed layer would heat at the rate of 0.1 K/day (3 K/month).

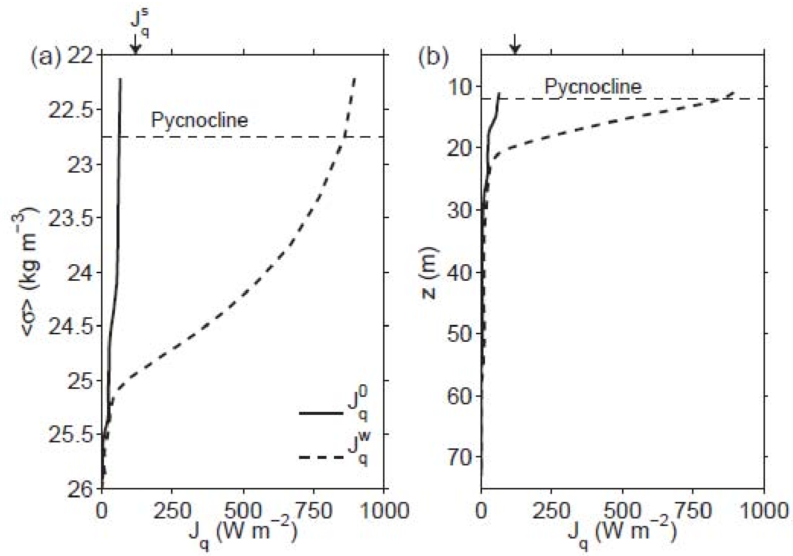

Figure 3 (a) Average downward heat flux profiles as a function of density for background conditions (solid line) and waves (dashed line). Background conditions are based on profiles taken just prior to wave groups, and a 24 hour stationary profiling series with periods of waves removed. (b) Same as in panel (a), but plotted as a function of depth. Profiles have been filtered to include scales larger than 7 m. Arrows show the average surface heat flux.

IMPACT/APPLICATION

Experimental verification of the existence, sign and magnitude of the bottom pressure signature of NLIWs indicates what we understand the physical structure of the wave pressure signal. This permits extension of the measurement to practical applications such as simple wave detection and more scientific applications such as inexpensive multi-component wave antennae.

Our analysis of energy transformations over the NJ shelf will contribute to global evaluations of NLIW energetics. Our analysis of cross-isopycnal heat fluxes due to the waves indicates their importance to maintaining shelf systems (including, by extension, biochemical systems).

RELATED PROJECTS

The SW06 experiment involved collaboration with a wide range of PIs, including physical oceanographers (D Farmer (URI), L Armi (SIO), J Klymak (UVic), J Nash, B Smyth (OSU)) and acousticians (M Badiey (Delaware), DJ Tang (APL/UW), A Lavery (WHOI)).

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Moum, J.N., D.M. Farmer, E.L. Shroyer, W.D. Smyth and L. Armi, 2007: Dissipative losses in nonlinear internal waves propagating across the continental shelf, *J. Phys. Oceanogr.*, 37, 1989-1995.

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